# Aquarius CAP Algorithm and Data User Guide

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The Aquarius geophysical model functions for the CAP algorithm were developed by Dr. Wenqing Tang; the operational setup and processing of the CAP algorithm was completed by Dr. Alex Fore; the setup of data portal and data transfer was performed by Mrs. Akiko Hayashi.

Document Change Log

| **Date** | *Page Numbers* | **Version** | **Changes/Comments** |
|---|---|---|---|
| February 20, 2013 | Page 8 | 2.0 | Updated the cost function by adding two additional terms to constrain the wind speed and direction retrieval |
| February 20, 2013 | Page 11 | 2.0 | Add 10 to the flag to indicate possible rain contamination |
| February 20, 2013 | Pages 5 and 6 | 2.0 | Include the significant wave height as a modeling parameter for radar backscatter and excess emissivity |
| June 20, 2014 | All | 3.0 | Include the rain corrections to GMFs of radar backscatter and excess emissivity and provide references to the articles on product validation results. |

## Contents

# I. PURPOSE

This document provides an overview of the Combined Active-Passive (CAP) Algorithm for the sea surface roughness correction to enable the retrieval of sea surface salinity, wind speed and direction from Aquarius data. The results from the CAP algorithm are output to files in HDF5 format. This document describes the datasets in the files and their format.

## II. INTRODUCTION

The measurement principle for salinity remote sensing is based on the response of the L-band (1.413 GHz) sea surface brightness temperatures ($T_B$) to sea surface salinity [1]. The influence of wind speed on L-band $T_B$ has been shown to be about 0.2 to 0.3 K for one $m.s^{-1}$ change in wind speed by many field studies [2-7]. To achieve the required 0.2 practical salinity unit (psu) accuracy for Aquarius mission, the impact of sea surface roughness (e.g. wind-generated ripples, foam, and swells) on the observed brightness temperature has to be accurately corrected, ideally to better than one tenth of a degree Kelvin.

The Aquarius radiometer and scatterometer have been fully operating since August 25, 2011. Other than the interruptions caused by a few spacecraft maneuvers, the data acquisition has been continuous. The Aquarius instrument has three antenna beams, operating at about 29, 38 and 46 degrees [8]. Each antenna beam has one radiometer (1.413 GHz), which can acquire the first three Stokes parameters of microwave radiation. The antenna feeds are shared with the scatterometer (1.26 GHz), which acquire the normalized radar cross sections ($\sigma_0$) for co- and cross-polarizations, including VV, HH, VH and HV polarizations.

The Aquarius radiometers make partial polarimetric measurements for the first three Stokes parameters, I, Q, and U [9]. I and Q correspond to the sum and difference of the vertically polarized brightness temperature ($T_{BV}$) and horizontally polarized brightness temperature ($T_{BH}$). $T_{BV}$ and $T_{BH}$ are measures of the power of the vertically polarized electrical field ($E_V$) and horizontally polarized electric field ($E_H$), while the third and fourth Stokes parameters (U and V) signify the correlation between $E_V$ and $E_H$:

$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \begin{bmatrix} T_{BV} + T_{BH} \\ T_{BV} - T_{BH} \\ U \\ V \end{bmatrix} \propto \begin{bmatrix} \langle |E_V|^2 \rangle + \langle |E_H|^2 \rangle \\ \langle |E_V|^2 \rangle - \langle |E_H|^2 \rangle \\ 2\,\mathrm{Re}\langle E_V E_H^* \rangle \\ 2\,\mathrm{Im}\langle E_V E_H^* \rangle \end{bmatrix} \quad \textbf{(1)}$$

The angular brackets denote the ensemble average of the enclosed quantities. Aquarius does not measure the fourth Stokes V.

The matchup data using either SSM/I or NCEP wind for binning have been used to develop the geophysical model functions (GMF) for Aquarius [13], which relate the microwave backscatter or excess surface emissivity to the wind speed ($w$) and direction ($\phi$). In addition, we include the NOAA WaveWatch-III Significant Wave Height (SWH) to develop the GMF and as ancillary for retrieval. We use the following cosine series for the modeling of radar data:

$$\sigma_{VV}(w,\phi,SWH) = A_{0VV}(w,SWH)[1 + A_{1VV}(w)\cos\phi + A_{2VV}(w)\cos 2\phi] \quad \textbf{(2)}$$

$$\sigma_{HH}(w,\phi,SWH) = A_{0HH}(w,SWH)[1 + A_{1HH}(w)\cos\phi + A_{2HH}(w)\cos 2\phi] \quad \textbf{(3)}$$

Here $\sigma_{VV}$ and $\sigma_{HH}$ are the normalized radar backscatter cross-sections for V-transmit/V-receive and H-transmit/H-receive, respectively. The modeling coefficients in Eqs. (2) and (3) are illustrated in [13, 20].

For the radiometer model function, we use the following expressions to characterize the dependence of excess surface emissivity on wind speed, wind direction and SWH:

$$\Delta e_V(w,\phi,SWH) = e_{V0}(w,SWH) + e_{V1}(w)\cos\phi + e_{V2}(w)\cos 2\phi \quad \textbf{(4)}$$

$$\Delta e_H(w,\phi,SWH) = e_{H0}(w,SWH) + e_{H1}(w)\cos\phi + e_{H2}(w)\cos 2\phi \quad \textbf{(5)}$$

$$U(w,\phi) = U_1(w)\sin\phi + U_2(w)\sin 2\phi \quad \textbf{(6)}$$

The third Stokes parameter for the L-band frequency is modeled by the sine function of the wind direction. The modeling coefficients for $\Delta e_V$ and $\Delta e_H$ are illustrated in [13, 20].

Given the GMF for excess surface emissivity, following are the complete descriptions of the radiometer model function, which relates the brightness temperatures to surface salinity (SSS), SST, wind speed, wind direction and SWH:

$$T_{BV}(SSS,SST,w,\phi,SWH) = T_{BVflat}(SSS,SST) + SST\cdot\Delta e_{BV}(w,\phi,SWH) \quad \textbf{(7)}$$

$$T_{BH}(SSS,SST,w,\phi,SWH) = T_{BHflat}(SSS,SST) + SST\cdot\Delta e_{BH}(w,\phi,SWH) \quad \textbf{(8)}$$

$$U(SSS,SST,w,\phi) = U_1(w)\sin\phi + U_2(w)\sin 2\phi \quad \textbf{(9)}$$

$T_{Bflat}$ is the brightness temperature for flat water surfaces computed using the water dielectric constant model [10, 11,16, 20] for given Reynolds SST and SSS. The subscript "p" stands for the polarization.

## III. Overview of CAP algorithm

The CAP algorithm retrieves the salinity and wind simultaneously by finding the best-fit solution to minimize the difference between the Aquarius data and the model functions described in Eqs. (2)-(9). The earlier versions of the CAP algorithm [12,13] use different functional forms for the cost function. After gaining more knowledge about the characteristics of the Aquarius L-band microwave data, particularly the weak response of radar backscatter to wind speed near the crosswind direction, we included the last two additional terms in Eq. (10) to constrain the wind speed and direction solutions primarily for near the crosswind directions. Detailed description of the CAP V3.0 retrieval algorithm is provided in [20]. The major updates to V2.0 include improved correction of reflected galactic radiation, geophysical model functions and cost function. The cost function for the CAP Version 3 algorithm is

$$F_{cap}(SSS,w,\phi)=\sum_{p=V,H}\frac{(T_{Bp}-T_{Bpm})^2}{\Delta T^2}+\sum_{p=V,H}\frac{(\sigma_{0p}-\sigma_{0pm})^2}{(\gamma_p\sigma_{0p})^2}+\frac{(w-w_{NCEP})^2}{\Delta w^2}+\frac{\sin^2[(\phi-\phi_{NCEP})/2]}{\delta^2}$$

**(10)**

The weighting factors for the Aquarius data are set according to the expected measurement and modeling uncertainties. We let $\Delta T$ be the Noise-Equivalent-Delta-T (NEDT) of radiometer and $\gamma_p$ be1.4 times of the radar measurement sensitivity ($k_{pc}$). The values of NEDT and $k_{pc,}$ a function of signal-to-noise ratio, have been pre-computed and saved in the Aquarius L2 data files. The value of $\Delta w$ is 1.5 ms$^{-1}$, a rather weak constraint because the accuracy of CAP wind speeds is estimated to be about 0.7 ms$^{-1}$ [13]. The value of $\delta$ is 0.2, which will constrain the wind direction to be within an RMS deviation of 11 degrees from the NCEP wind direction. Our previous analysis [13] indicates that the directional accuracy of the CAP algorithm is about 10 degrees or better for wind speeds of 15 ms$^{-1}$ or above. The effect of the last term will not impact the accuracy of the CAP wind direction retrieval for high winds, but will help constrain the wind direction solution for low winds, for which the L-band data have a weak response to wind direction.

For the Aquarius data, we applied the conjugate gradient technique using a modified Levenberg-Marquardt algorithm [14] to find the local minima of $F_{cap+}$. There are in general four local minima (ambiguous solutions). This is due to the expansion of the model function for wind direction by including up to the second harmonics of the cosine series. For each given wind speed solution, there will in general be four direction solutions, except when the relative wind direction is along upwind, or downwind or crosswind. This can be easily understood by considering the special case when the $A_1$ coefficients are zero in the model functions. If the first harmonic coefficient $A_1$ is zero, these four solutions, corresponding to the inversion of $\cos 2\phi$, are $\phi$, $-\phi$, $\phi+180^o$ and $180^o-\phi$. If $A_1$ and $e_{B1}$ are small, then the third and fourth solutions will shift slightly away from $\pm\phi+180^o$. Note that because the cosine series are even functions, the solution pair, $\pm\phi$, will produce identical values for model functions, and consequently lead to the same SSS and wind speed solutions. The same is true for the $\pm\phi+180^o$ solution pair.

A nominal technique developed for the current or past spaceborne wind scatterometer and radiometer missions is the use of numerical weather analysis, such as NCEP or European Center for Medium Range Forecasts (ECMWF), or special wind features to assist the selection of solutions [15]. For salinity and wind speed retrievals, the discrimination of ambiguities is a less challenging issue than ocean wind scatterometers or radiometers because what is needed is to separate the four solutions into two pairs, $\pm\phi$ and $\pm\phi$ $+180^o$, which are separated by about 180 degrees. As previously discussed, each pair will have the same SSS and wind speed values. In our analysis, we use the numerical wind analyses to select the solution by selecting the solution with the closest wind direction to NCEP.

## IV. RAIN CORRECTION

Based on the analysis of the L-band radiometer/radar residual signals under rainy conditions after accounting for roughness due to wind and flat surface emissivity [16], we introduced a rain correction term for radar/radiometer GMF. For radar backscatter, we have

$$\sigma_{0,p}(w, \phi, SWH, RR) = \sigma_{0,p}^{norain}(w, \phi, SWH) + \sigma_{0,p}^{rain}(w, RR) \quad (11)$$

where $\sigma_{0,p}^{norain}$ is given by Eqs. (2) & (3) (with p denotes VV or HH). The rain correction term $\sigma_{0,p}^{rain}$ is modeled empirically by binning the difference between measured $\sigma_{0,p}$ and $\sigma_{0,p}^{norain}$ as a function of surface rain rate (RR) and wind speed (w).

Similarly for radiometer, we have,

$$\Delta e_p(w, \emptyset, \text{SWH}, RR) = \Delta e_p^{norain}(w, \phi, SWH) + \Delta e_p^{rain}(w, RR) \quad (12)$$

where $\Delta e_p^{norain}$ is given by Eqs. (4) & (5) for V-pol and H-pol respectively. The rain correction term $\Delta e_p^{rain}$ is modeled from binning the difference between measured brightness temperature and $\Delta e_p^{norain}$, with emissivity from the flat surface calculated from the sea surface temperature (SST) [17] and HYCOM SSS [18]. HYCOM assimilates the ocean surface's space-time variability on SST and SSH (sea surface height) obtained from satellite observations, the salinity information assimilated is from profiling floats, e.g. ARGO, which mainly operate at 5 meters below the surface. Therefore HYCOM SSS does not represent the first centimeter or skin salinity, rather the bulk salinity in the upper few meters. Under persistently rainy conditions, there are often near surface stratification. Hence it is expected that the rain-dilution effect on HYCOM SSS will be reduced with respect to the effect on the salinity sampled by the radiometer at 1-2 cm depth. As a consequence, the rain correction on radiometer $T_B$ is likely to be overestimated and the salinity retrieved is likely to be closer to a "bulk" salinity as HYCOM SSS than to surface salinity [21].

The CAP retrieval software can be easily modified to account for additional correction in GMFs. Under rainy conditions, the CAP algorithm is run in parallel using GMF with or without the rain correction terms. The ancillary rain rate data used are based on SSM/I or WindSAT measurements, which is collocated with each Aquarius data block within one hour and 12.5 km radius.

## V. VALIDATION

We have validated the accuracy of retrieval using the CAP algorithm for simultaneous wind and salinity retrieval. For wind speed validation, the results have been published by Fore et al. [19]. For salinity validation, extensive comparison has been made with mooring data and Argo gridded data products by Tang et al. [21, 22].

## VI. CAP L2 DATA AND FORMAT

The Aquarius CAP L2 files contain the CAP algorithm outputs and a few datasets in the Aquarius L2 data files, in HDF format.

### A. *File name convention*

The file names are similar to the Aquarius L2 files. The first part of the file name is the same as that in the Aquarius L2 files. We added the extension '.cap' to it.

For example, Q2012001012500.L2_SCI_V3.0.cap, is the file for the data pass started at 01:25:00 UT on day 1, 2012. "L2_SCI_V3.0" indicates the version of Aquarius L2 files used for the CAP processing.

### B. *Description of datasets in HDF*

The datasets in the HDF5 files are part of the root file, not in a "Aquarius Data" group. Each dataset has 4083 blocks for 3 antenna beams.

A simple way to separate the data from ascending and descending passes for ocean observations is to use the first array index of the dataset. If the first array index is smaller (greater) than 2042, then the data are from ascending (descending) orbits.

#### 1) *CAP outputs*

The CAP data and critical time and location data sets are outlined below.

| Dataset | Size (Block, Beam) | Format | Unit | Valid range | Description |
|---|---|---|---|---|---|
| Sec | Dataset {4083} | double float | Seconds | 0.d0 to 86399.999999d0 | Block time in seconds of day |
| beam_clat | Dataset {4083, 3} | float | Degree | -90 to 90 | Latitude of footprint |
| beam_clon | Dataset {4083, 3} | float | Degrees | -180 to 180 | Longitude of footprint |
| SSS_cap | Dataset {4083, 3} | float | Psu | 0 to 50 | SSS from the CAP algorithm |
| SSS_cap_rc | Dataset {4083,3} | Float | Psu | 0 to 50 | SSS from the CAP with rain correction if RR>0; SSS_cap_rc is identical to SSS_cap if no rain (RR=0), or there is no rain data matchup with Aquarius |
| SSS_cap_v | Dataset {4083, 3} | float | Psu | 0 to 50 | SSS retrieved from the V-pol TB using the scat_wind_speed for excess surface emissivity correction |
| wind_speed_cap | Dataset | float | Meters | Greater than 0 | Wind speed retrieved |

| | | | | | |
|---|---|---|---|---|---|
| | {4083, 3} | | per sec | | from the CAP algorithm |
| wind_dir_cap | Dataset {4083, 3} | float | Degrees | -180 to 180 | Wind direction retrieved from the CAP algorithm |
| cap_flag | Dataset {4083, 3} | H5T_NATIVE_UCHAR | | 0 to 5, 10 to 15 and 100* | Flag for CAP retrieval |
| scat_wind_speed | Dataset {4083, 3} | float | Meters per sec | Greater than 0 | Wind speed retrieved from the Aquarius scatterometer data using the NCEP wind direction as ancillary information |

wind_dir_cap is the wind direction retrieved from the Aquarius data, and is the direction from with respect to the north in clockwise direction. Its error is less than 20 degrees RMS at greater than 12 m/s wind speeds for beam 1 and 10 m/s for beams 2 and 3.

cap_flag: The flag for CAP algorithm retrieval with the values of 0, 1, and 2 for valid SSS retrieval and 3 and 4 for invalid SSS retrieval. If the matchup rain rate (RR) from SSMIS or WindSat is greater than zero, we add 10 to the flag to indicate possible rain contamination.

- 0 for abs(wind_speed_cap-anc_wind_speed) <15 m/s
- 1 for abs(wind_speed_cap-anc_wind_speed) <30 m/s
- 2 for abs(wind_speed_cap-anc_wind_speed) >30 m/s
- 3 for wind_speed_cap <0 or sss_cap < 0 or sss_cap > 50
- 4 for no retrieval
- 5 for TBerr >= 0.4 K, where $TB_{err} = \sqrt{\left(TB_V^{meas.} - TB_V^{mod.}\right)^2 + \left(TB_H^{meas.} - TB_H^{mod.}\right)^2}$
- 10 for abs(wind_speed_cap-anc_wind_speed) <15 m/s and RR>0
- 11 for abs(wind_speed_cap-anc_wind_speed) <30 m/s and RR>0
- 12 for abs(wind_speed_cap-anc_wind_speed) >30 m/s and RR>0
- 13 for wind_speed_cap <0 or sss_cap < 0 or sss_cap > 50 and RR>0
- 14 for no retrieval and RR >0
- 15 for TBerr >= 0.4 K and RR >0

*We added 100 to the cap_flag if abs(rad_TaV-rad_TfV)>= 1 or abs(rad_TaH-rad_TfH)>= 1.

*2) Carryover from Aquarius L2 files*

The following are datasets carried over from the Aquarius L2 files. They are included for ease of comparison with the CAP products.

| Dataset | Size (Block, Beam) | Unit | Description |
|---|---|---|---|
| SSS | Dataset {4083, 3} | Psu | SSS in the Aquarius L2 files |
| anc_SSS | Dataset {4083, 3} | Psu | Ancillary (HYCOM) SSS in the Aquarius L2 files |
| anc_surface_temp | Dataset {4083, 3} | Kelvin | SST in the Aquarius L2 files |

| | | | |
|---|---|---|---|
| anc_wind_speed | Dataset {4083, 3} | Meters per sec | Ancillary (NCEP) wind speed in the Aquarius L2 files |
| anc_wind_dir | Dataset {4083, 3} | Degrees | Ancillary wind direction (NCEP) in the Aquarius L2 files |
| scat_land_frac | Dataset {4083, 3} | | Scatteroemter land fraction in the Aquarius L2 files (unitless between 0 and 1) |
| scat_ice_frac | Dataset {4083, 3} | | Scatteroemter ice fraction in the Aquarius L2 files (unitless between 0 and 1) |
| land_frac | Dataset {4083, 3} | | Radiometer land fraction in the Aquarius L2 files (unitless between 0 and 1) |
| ice_frac | Dataset {4083, 3} | | Radioemter ice fraction in the Aquarius L2 files (unitless between 0 and 1) |

## VII. CAP L3 DATA AND FORMAT

The Aquarius CAP L3 data contain monthly and weekly maps on 1°x1° grid for both SSS_cap and SSS_cap_rc, in netcdf format. L3 data are created using Gaussian weighting with half-power and searching distances at 75 and 111 km, respectively. The filtering criteria for transferring data from Level 2 to Level 3 are: land_frac < 0.01, ice_frac < 0.0005, anc_surface_temp > 273, and cap_flag < 3 or 10<=cap_flag < 13, in addition to checking the radiometer flag included in Aquarius L2 files for non-nominal navigation (bit-12), and pointing anomaly (bit-16).

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